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Published in:
2010 Conference on (OFC/NFOEC) Optical Fiber Communication (OFC), collocated National Fiber Optic Engineers Conference

Publication date:
2010

Document Version
Publisher's PDF, also known as Version of record

Citation (APA):
Galili, M., Mulvad, H. C. H., Oxenløwe, L. K., Hu, H., Palushani, E., Clausen, A., & Jeppesen, P. (2010). Generation and detection of 2.56 Tbit/s OTDM data using DPSK and polarisation multiplexing. In *2010 Conference on (OFC/NFOEC) Optical Fiber Communication (OFC), collocated National Fiber Optic Engineers Conference* (pp. 1-3). IEEE.

Generation and Detection of 2.56 Tbit/s OTDM Data using DPSK and Polarisation Multiplexing

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Abstract: Error free and low penalty generation and detection of 2.56 Tbit/s serial data is demonstrated. 1.28 Tbaud pulses are modulated with DPSK and polarisation multiplexed to achieve 2.56 Tbit/s with record low penalty.

OCIS codes: (060.4370) Nonlinear optics, fibers; (060.2330) Fiber optics communications

1. Introduction

In recent years there has been an increasing interest in identifying schemes for optical data transmission which can supplement or substitute the schemes currently used in optical communication systems. This is done in the pursuit of higher data capacity and lower power consumption. Optical Time Division Multiplexing (OTDM) is one of the technologies which might potentially offer both of these benefits for many applications [1].

OTDM enables symbol rates beyond 640 Gbaud, and can be used with polarisation multiplexing (pol-mux) to generate a serial binary data rate of e.g. 1.28 Tbit/s [2]. To further increase the data rate in a single wavelength channel, modulation formats enabling several bits per symbol have been used in combination with OTDM and pol-mux. This strategy has led to a few demonstrations of single channel bit rates of 2.56 Tbit/s or more. The first demonstration used DQPSK and pol-mux of 640 Gbaud to achieve a bit rate of 2.56 Tbit/s [3]. Recently by changing the modulation format to 8PSK combined with coherent detection an error free data rate of 3.56 Tbit/s was demonstrated, assuming UFEC [4]. Finally, using DQPSK and pol-mux at a symbol rate of 1.28 Tbaud an error free bit rate of 5.1 Tbit/s in a single wavelength channel was achieved in [5].

In this paper, we investigate the performance of 1.28 Tbaud pulses using binary modulation (DPSK) and pol-mux to achieve 2.56 Tbit/s with record low penalty. We demonstrate generation and detection of 2.56 Tbit/s with error free performance (BER<10^{-9}) and a total penalty in receiver sensitivity of no more than 3 dB compared to the original 10 Gbit/s reference. This is the best performance and lowest penalty ever achieved in a single channel signal reaching more than 2 Tbit/s.

2. Principle and experimental procedure

The experimental set-up is shown in Fig. 1. The 2.56 Tbit/s OTDM transmitter is based on an Erbium-glass oscillator mode locked laser (ERGO), emitting a 10 GHz optical pulse train at 1542 nm with 1.5 ps FWHM. The optical pulses are spectrally broadened in a dispersion-flattened highly non-linear fibre (DF-HNLF1, 400 m with γ~10.5 $W^{-1}km^{-1}$, dispersion D=-0.45 ps/(nm km) and slope S=0.0057 ps/(nm^2 km) at 1550 nm) and subsequently filtered by a 5 nm band-pass filter (BPF) centred at 1550 nm. The optical spectra after broadening in DF-HNLF1 and after the 5 nm BPF are shown in Fig. 2a. The offset filtering effectively increases the contrast in the pulse train by suppressing undesired components present in the ERGO output. The output from the first compression stage is

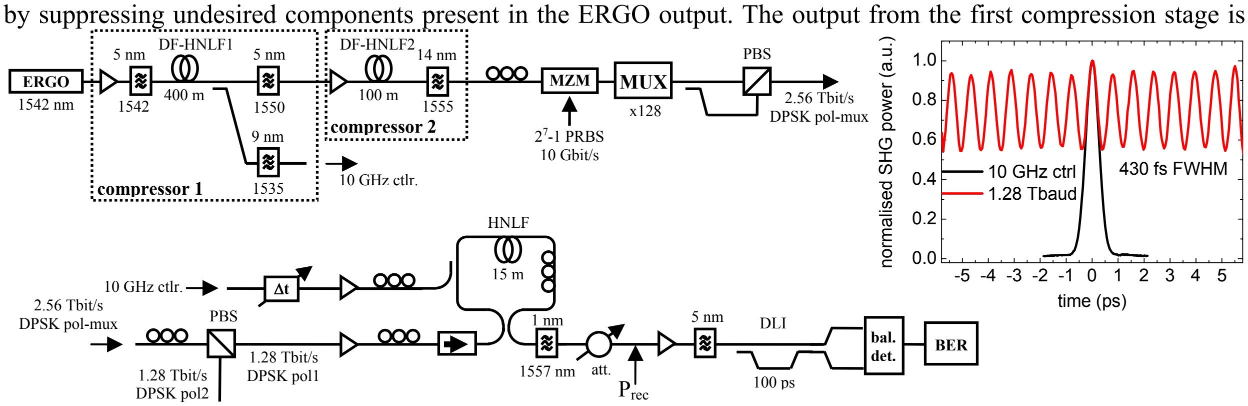

Fig. 1: Setup for generating and detecting 2.56 Tbit/s DPSK pol-mux. Autocorrelation shows multiplexed data pulses at 1.28 Tbaud and 10 GHz control pulses used demultiplexing.

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also used to generate the 10 GHz control pulses (ctrl) to be used for demultiplexing. These are extracted using a 9 nm BPF centred at 1535 nm. The pulse train at 1550 nm is further compressed by spectral broadening in DF-HNLF2 (100 m with γ~10.5 $W^{-1}km^{-1}$, D=-1.06 ps/(nm km) and S=0.004 ps/(nm^2 km)) and filtering with a 14 nm BPF at 1555 nm. The optical spectra after broadening in DF-HNLF2 and after the 14 nm BPF are shown in Fig. 2b. The compressed pulses are then data modulated with 10 Gbit/s DPSK data using a chirp free Mach-Zehnder modulator (MZM) encoding a 2^7-1 PRBS pattern. The data pulses are then OTDM-multiplexed from 10 Gbit/s up to 1.28 Tbit/s in a PRBS maintaining multiplexer (MUX) based on passive fibre delay lines. The autocorrelation in Fig. 1 shows that the multiplexing is performed with virtually no variation between the OTDM tributaries. Finally, the 1.28 Tbit/s DPSK signal is polarisation multiplexed (POL-MUX) by splitting the signal in a 3 dB coupler and combining the two outputs in a polarisation beam splitter (PBS). This results in a polarisation multiplexed 2.56 Tbit/s data signal. In this back-to-back demonstration the 2.56 Tbit/s data signal is then detected in the receiver setup as shown in the lower part of Fig. 1. Firstly, the PBS separates the two 1.28 Tbit/s polarisation components (pol1 and pol2) of the incoming 2.56 Tbit/s pol-mux data. A nonlinear optical loop mirror (NOLM) is then used to demultiplex the 1.28 Tbit/s data down to the individual 10 Gbit/s tributary channels. The NOLM operation is based on cross-phase modulation in a 15 m HNLF (γ~10.5 $W^{-1}km^{-1}$, zero-dispersion wavelength λ_0 ~1545 nm and S=0.015 ps/(nm^2 km)) using the 10 GHz ctrl pulses at 1535 nm. The optical spectra of the data and control pulses in the NOLM are shown in Fig. 2c. The demultiplexed 10 Gbit/s signal is extracted using a 1 nm BPF at 1557 nm to suppress the control pulses (c.f. Fig. 2c), and finally detected using a 10 Gbit/s DPSK receiver. Here, the 10 Gbit/s DQPSK data are preamplified, filtered and then demodulated using a 1-symbol delay interferometer (DLI). The DLI output is detected using a balanced photo-detector, and then injected into a 10 Gbit/s error-detector for bit error rate (BER) evaluation.

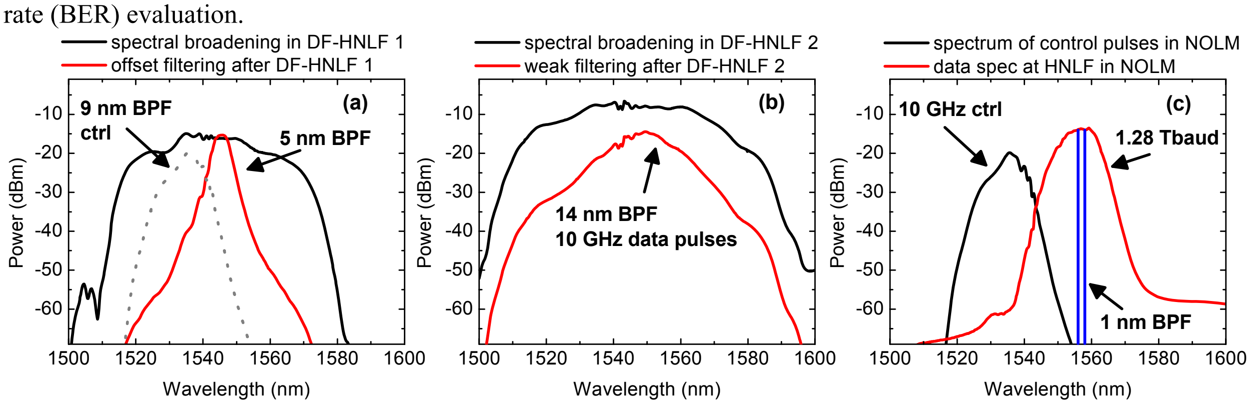

Fig. 2: (a) Spectral broadening in DF-HNLF 1 and subsequent offset filtering. (b) Spectral broadening in DF-HNLF 2 and subsequent slight spectral shaping by 14 nm filter. (c) Data spectrum in NOLM after shaping in EDFAs and control pulses used for demultiplexing.

3. Results and discussion

Fig. 2. shows optical spectra describing the key optical processing required in order to create and detect the 1.28 Tbaud pulses used in this demonstration. In Fig. 2a the operation of the first compression stage is shown. The key function of this stage is to suppress trailing pulses emitted by the ERGO laser and at the same time compress the pulses to less than 1 ps FWHM. In this way an optimised input to the final compression stage is extracted from the broadened spectrum using a 5 nm BPF centred 8 nm away from the original ERGO output. The first compression stage is also used to generate the demux control pulses at 1535 nm. These are extracted with a 9 nm BPF generating pulses of ~430 fs FWHM which is close to the target pulse width for the data pulses, however, the control pulses have insufficient suppression of the trailing pulses to allow stable multiplexing. Fig. 2b shows the spectral broadening and filtering in the second compression stage. The output is filtered broad enough to allow significant spectral shaping by the EDFAs used to compensate the loss throughout the rest of the setup. The spectrum of the data pulses in the NOLM demultiplexer corresponding to the autocorrelation in Fig. 1 is shown in Fig. 2c. For this spectrum of the data pulse a pulse width of ~410 fs FWHM is measured giving a time bandwidth product (TBP) of ~0.5 for the data pulses in the demultiplexer. This is only 14% above the transform limit for a Gaussian pulse. It is expected that this low TBP can be achieved for the data pulses throughout the setup if gain flattened EDFAs were used instead of the standard EDFAs that were available for this demonstration. Fig. 2c also shows the wavelength allocation of control and data signals in the demultiplexer where a 1 nm BPF is used to suppress the control pulses at the output by selecting a part of the data spectrum which does not overlap with the control pulses.

Fig. 3 shows the BER results for both the 1.28 Tbit/s DPSK signal and for the polarisation multiplexed signal achieving 2.56 Tbit/s. In both cases eight consecutive OTDM channels were measured in order to estimate the variation in performance between the multiplexed channels. The 10 Gbit/s reference signal is measured by launching the output of the MZM into the DPSK receiver and thus bypassing both the multiplexer and demultiplexer. The eye diagram (a) in Fig. 3 shows the clear and open eye of the 10 Gbit/s reference signal which is confirmed by a receiver sensitivity of ~-41 dBm at a BER of 10^{-9}. For the single polarisation 1.28 Tbit/s signal the eight channels have a variation in receiver sensitivity of only 0.5 dB and they have an average penalty of 2.5 dB compared to the 10 Gbit/s reference. For the polarisation multiplexed 2.56 Tbit/s signal BER curves for eight channels in each polarisation are shown with corresponding eye diagrams in Fig. 3 (b) and (c). The performance of the signal is almost unchanged by the polarisation multiplexing resulting in 0.2 dB excess penalty in one polarisation and 0.5 dB in the other and a slight increase in channel variation in one polarisation. For all detected signals and channels there is no indication of an error floor down to a BER of at least 10^{-10}. The 2.5 dB to 3 dB penalty in receiver sensitivities is attributed mainly to reduced OSNR caused by the EDFAs in the setup. To reduce this penalty the losses in the setup for generating and detecting the signal will have to be reduced.

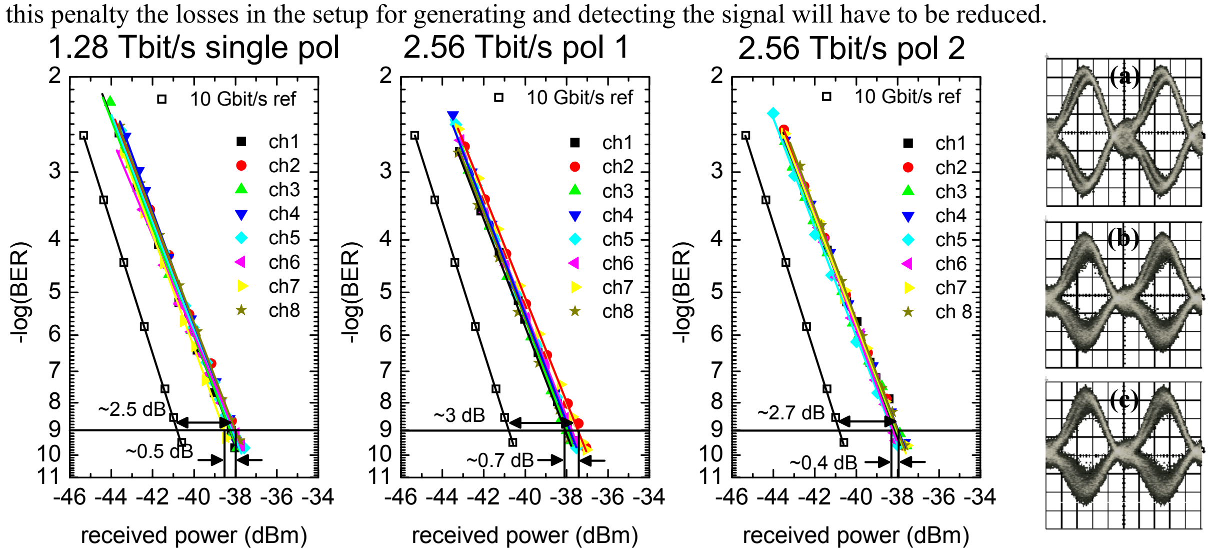

Fig. 3: Bit error rate results for 8 consecutive channels for both the single polarisation 1.28 Tbit/s signal and for each polarisation in the polarisation multiplexed 2.56 Tbit/s signal. (a) 10 Gbit/s reference after demodulation and differential detection. (b) Pol 1 of 2.56 Tbit/s after demux. (c) Pol 2 of 2.56 Tbit/s after demux.

4. Conclusion

We have demonstrated error free and low penalty generation and detection of a 2.56 Tbit/s DPSK pol-mux signal in a single wavelength channel. All the detected signals achieve a BER < 10^{-9} and exhibit no sign of an error floor. We achieve less than 1 dB variation in receiver sensitivity between the measured OTDM channels and less than 3 dB penalty compared to the 10 Gbit/s reference signal. This constitutes the best performance and lowest penalty ever achieved in a single channel signal reaching more than 2 Tbit/s. This demonstration makes clear that low penalty generation and detection of single channel data signals of several Tbit/s is feasible using a high symbol rate and simple modulation format.

5. Acknowledgments

This work is supported by Danish NABIIT grant 2106-06-0052, project Nano-com.
All HNLF is kindly provided by OFS Fitel Denmark Aps.

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